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An Analysis of Gas Kick Removal From the Marine Riser

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ABSTRACT

This paper presents an analysis of the dynamic pressures imposed on the marine riser and diverter line during the gas removal from a riser-diverter system. The occurrence of formation gas in the riser may lead to a drilling accident known as "riser blowout" that can cause the collapse of the riser pipe in addition to the inherent risk of fire.

This analysis makes use of a numerical simulator, detailed in this study, that models the pressure and flow rate behavior in the riser-diverter system. The simulator is based on the numerical solution of a system of flow equations for a two-phase mixture moving upward in the riser-drill pipe annulus. The model accounts for the acceleration of the drilling fluid flowing ahead the two-phase mixture and the sonic flow at the diverter line exit.

In this paper, the approach of circulating a fluid through the lower portion of the marine riser to displace the gas up and inside the riser and diverter system is extensively investigated. Through a sensitivity analysis, the effects of pertinent parameters - especially the circulation rate - on the pressures generated inside the riser-diverter system during the gas removal process are discussed. Non-circulation situations are also studied.

References and figures at the end of paper

INTRODUCTION

The need for new hydrocarbon reserves has been motivating the oil industry to drill in very deep waters. In such circumstances, the use of floating rigs is required so that the blowout preventers are located at the seabed with a marine riser linking them to the vessel. A typical equipment configuration of the deepwater drilling is shown in Figure 1.

If a gas kick is taken in a deepwater drilling operation, the recommended action is to close the BOP rams immediately. This procedure is sustained by several field case accidents and by theoretical studies reported in the literature. In one of these studies¹, it was shown that if the gas is allowed to flow in an uncontrolled manner through the diverter line, the generated pressures can lead to equipment failure in two different moments. As illustrated in Figure 2, in the beginning of the riser unloading process, high pressures (420 psi) are encountered which may cause dangerous gas leak at the diverter. Later on, the riser internal pressure drops dramatically to 150 psi. This low internal pressure may cause collapse of the lowest joints of the marine riser.

Even following the appropriate practice of closing the BOP, some formation gas may enter the marine riser. This can happen due to delay in closing the BOP after kick detection or due to the gas trapped in the subsea stack and released to the riser, after a successful gas kick removal from the wellbore. In both cases, the gas rises and, as it expands, a large amount of drilling fluid

is expelled overboard. This sequence of events may result in explosion and fire in the drilling platform and/or riser collapse.

The main scope of this study is to predict and analyze the pressure behavior during the gas kick removal from the marine riser using a dynamic computer model that reflects more realistically the phenomenon.

ASSUMPTIONS AND MODEL EQUATIONS

Figure 3 shows the situation that might occur following the subsea stack closure. If the rig is equipped with a boost line, the mud can be pumped through it to circulate the gas out of the riser-diverter system. The prediction of the pressures generated inside the system during this circulation is the main objective of the computer model.

To facilitate the elaboration of this numerical simulator, the calculation procedure has been broken down into two submodels: a) the riser submodel for the upward vertical flow through the riser-drill string annulus and b) the diverter submodel for the horizontal flow inside the diverter line.

Riser Submodel

Initially, the riser submodel deals with a two-phase gas-mud mixture that flows upward displacing the unmixed mud out of the riser-diverter system. After the gas reaches the diverter, only a two-phase mixture is considered by the model.

To assist in the development of the riser submodel, the following assumptions and considerations have been made: a) the drilling fluid is incompressible and follows the power law rheological model; b) the temperature is known and constant over the riser length; c) the gas solubility in the mud is negligible; d) the initial gas volume and gas concentration distribution in the riser is user specified; e) the two-phase mixture accounts for liquid hold-up, gas concentration distribution and two-phase flow friction factor; and f) the acceleration pressure drop of the unmixed liquid flowing ahead the two-phase mixture is considered.

For the two-phase region, the pressures are found by solving a system of five nonlinear equations that represents the unsteady state flow of a two-phase mixture. The simulator makes use of the Eulerian approach for solving the system of equations. That approach consists in dividing the marine riser into fixed cells of equal lengths and in calculating the dependent flow variables (gas and liquid velocities, gas density, pressure and the liquid hold-up) at cell

boundaries. The independent variables are the displacement time and position along the flow path. The five governing equations are as follows:

1) Liquid Material Balance Equation

$$M_{lc} = M_{lp} + [(H \cdot v_l \cdot D_l)_{dc} - (H \cdot v_l \cdot D_l)_{uc}] \cdot A \cdot \Delta t \quad \dots\dots\dots(1)$$

2) Gas Material Balance Equation

$$M_{gc} = M_{gp} + [((1-H) \cdot v_g \cdot D_g)_{dc} - ((1-H) \cdot v_g \cdot D_g)_{uc}] \cdot A \cdot \Delta t \quad \dots\dots\dots(2)$$

3) Momentum Balance Equation

$$P_{uc} = P_{dc} - (G_{hyd} + G_{fri})_c \cdot \Delta x \quad (3)$$

4) Equation of State for the gas

$$D_{guc} = \frac{0.361 \cdot SG \cdot P_{uc}}{T \cdot Z} \quad \dots\dots\dots(4)$$

5) Equation that relates gas to liquid velocities

$$v_{guc} = C \cdot v_{mdc} + v_{sl} \quad \dots\dots\dots(5)$$

In the above equations, the frictional pressure gradient (G_{fri}) is calculated using the Beggs and Brill correlation² that includes a two-phase flow friction factor. The hydrostatic pressure gradient (G_{hyd}) is calculated by:

$$G_{hyd} = 0.052 \cdot [D_l \cdot H + D_g \cdot (1 - H)] \quad (6)$$

The constant C is assumed to be equal to 1 and accounts for the velocity profile of the liquid. The mixture velocity (v_m) is defined as:

$$v_m = v_l \cdot H + v_g \cdot (1-H) \quad \dots\dots\dots(7)$$

The gas slip velocity is a function of the two-phase flow regime. For bubble flow ($H > 0.85$), the Harmarthy's equation³ is applied:

$$v_{sl} = 0.4774 \cdot \left[\frac{(D_1 - D_g) \cdot ST}{D_1^2} \right]^{0.25} \cdot H^{0.5} \quad (8)$$

For slug flow ($0.75 > H > 0.45$), the Griffith and Wallis' equation⁴ is used:

$$v_{sl} = 1.637 \cdot K \cdot \left[\frac{(D_1 - D_g) \cdot DI}{D_1^2} \right]^{0.5} \quad \dots\dots(9)$$

where K is a coefficient that depends on the conduit geometry. In an annulus, it can be approximated by the following expression:

$$K = 0.354 - 0.037 \cdot R + 0.235 \cdot R^2 - 0.134 \cdot R^3 \quad \dots\dots(10)$$

where R is the ratio of the inner to outer diameters.

For annular flow ($H < 0.10$), the gas slip velocity is zero. Transition zones between these flow regimes were introduced to avoid numerical discontinuity in the solution. The slip velocities in these zones are calculated through linear interpolation.

The system of equations is solved at every cell boundary, from the bottom of the riser up to the interface between the mixture and the unmixed mud, to determine the flow variables, especially the pressure.

The unmixed mud flowing ahead the two-phase region is modelled by the expression:

$$P_{uc} = P_{dc} - (G_{hyd} + G_{fri} + G_{acc})_c \cdot \Delta x \quad (11)$$

where the frictional pressure gradient (G_{fri}) is calculated using the power law rheological model⁵. The acceleration pressure gradient (G_{acc}) is given by:

$$G_{acc} = 0.0016 \cdot D_1 \cdot \frac{\Delta v_1}{\Delta t} \quad \dots\dots(12)$$

where v_1 (the mud velocity) is given by the summation of the velocities due to the gas expansion in the two-phase region and to the displacing liquid in the riser-drill pipe annulus. In Equation 12, Δv_1 represents the difference between the mud velocities in the current and the previous time steps.

Diverter Submodel

While the interface mixture-unmixed mud is in the riser, only liquid flows through the diverter line. This situation is modelled by Equation 11 without the hydrostatic term (G_{hyd}). In this case, Δx is the diverter line length. Atmospheric pressure exists at diverter exit.

After the gas reaches the surface, only the two-phase mixture flows inside the diverter line and two conditions are possible at the diverter exit: a) during a short period, critical or sonic flow condition may take place at that location. This implies that the pressure at diverter exit is greater than the atmospheric pressure; b) for the rest of the gas production, subsonic condition prevails again at diverter exit.

The calculation procedure for the diverter submodel is based on a steady state numerical simulator developed at Louisiana State University and experimentally tested for 1-in., 2-in. and 6-in. diverter line. The model uses as input parameters the gas and mud mass flow rates that come from the riser to calculate the pressure drop inside the diverter line using the Duckler correlation⁶ for horizontal two-phase flow. The two-phase critical flow is modelled by an equation presented by Wallis⁷. Additional information about the LSU simulator can be found in References 1, 8 and 9.

CALCULATION PROCEDURE AND COMPUTER PROGRAM

The two submodels were coupled to produce a global algorithm for computing the flow variables at any point of the riser-diverter system. Basically, it follows the stepwise procedure described below:

- 1) Define the mud/mixture interface position and determine the time step size by dividing the cell length by the gas velocity at mixture leading edge calculated in the previous time step. This approach avoids the use of a front tracking technique since the mixture leading edge always coincides with a cell boundary.
- 2) Guess a bottom riser pressure and set the boundary conditions at the BOP: the gas velocity is zero, the liquid velocity is given by the displacing flow rate and the liquid hold-up is equal to 1.
- 3) Use the riser submodel and solve the system of equations at every cell boundary from the bottom of the riser to the mixture leading edge. Calculate the pressure drops for the mud flowing in the remainder of the riser and diverter line.

4) Sum all pressure drops up in the system. As atmospheric pressure prevails at diverter exit, this summation is the calculated bottom riser pressure. Compare it with the guessed value. If they are within an acceptable tolerance, repeat the process for the next time step. If not, guess another bottom riser pressure and repeat the process from Step 2.

This calculation procedure applies only before the gas reaches the diverter line entrance. Thenceforth, another procedure is used:

- 1) Define a time step size and guess a bottom riser pressure.
- 2) Use the riser submodel to find the pressure at diverter line entrance.
- 3) Determine the flow conditions (sonic or subsonic) and the pressure at the diverter line exit. Then, calculate the diverter line entrance pressure using the diverter submodel.
- 4) Compare the two calculated diverter line entrance pressures (Steps 2 and 3). If they are close enough, accept the guessed bottom riser pressure. If not, guess another bottom riser pressure and return to Step 2.

This calculation procedure was implemented in a FORTRAN computer program for use with a PC microcomputer.

RESULTS AND DISCUSSIONS

Table 1 presents the computer program input data used in the simulations. Two sets of initial conditions were investigated using the computer program. In the first set (Figures 4 to 8), a gas volume of 50 bbl for an initial gas concentration of 60 % and a non-circulation situation were considered. In the other (Figures 9 to 13), the gas volume was 36 bbl for an initial gas concentration of 45 % and three circulation conditions were analyzed.

Figure 4 shows the liquid volume in the riser as a function of time. It indicates that the mud volume stabilized at 770 bbl. Since the initial liquid volume in the riser-drill pipe annulus was 1162 bbl, the gas has displaced 392 bbl of mud out of the riser and the mud level has fallen down to 1094 feet. Under these conditions, the net external pressure acting on the riser at that point would be 484 psi. Considering the usual collapse safety factor of 1.125, the collapse resistance for a new pipe (22" OD x 21" ID ; X52) is 515 psi which is very close to the seawater external pressure.

Figure 5 and 6 display respectively the pressures at the bottom of the riser and at the riser mid-point (1500 feet).

Again, the external pressures at these two places are very close to the riser pipe collapse resistance. It should be noted that the net external pressures are very close for the three depth. The reason is the mud weight used in the simulations is equal to the seawater (8.5 ppg).

Figure 7 shows the pressure at the diverter line entrance. The maximum pressure is about 50 psi which is a small value when compared with those found in shallow gas blowouts. Figure 8 displays that sonic flow exists during a very short period and the pressure peak at the diverter line exit is very small (10 psi).

In Figure 9, the mud volumes inside the riser are presented for three circulation conditions. The worst case is for a non-circulation situation. The greater the displacing liquid flow rate, the least severe the conditions for a riser pipe collapse. Figures 10 and 11 also confirm that the circulation is beneficial to the riser pipe integrity during a "riser blowout".

Figures 12 and 13 illustrate the effect of the liquid displacing flow rate on the diverter system components. The highest circulation rate has imposed the highest loads on the diverter. However, they are negligible when compared with the loads generated during a shallow gas blowout. In Figure 13, it can be seen that the critical flow occurs at diverter exit for the three situations.

CONCLUSIONS

- 1) In deepwater drilling, the BOP should be closed instead of allowing the gas to flow through the riser-diverter system. This procedure avoids riser collapse and possible diverter failure.
- 2) Simulation results have demonstrated that pressure loads on the diverter system are not of concern in spite of critical flow occurrence at diverter line exit.
- 3) In a non-circulation situation, riser collapse is possible. Simulation results have confirmed that the gas should be circulated out of the riser at the highest flow rate available.
- 4) Numerical simulations indicated that, when the gas approaches the surface, it does not slip through the mud any longer but it pushes the mud out of the riser-diverter system.

NOMENCLATURE

A	=	riser cross-sectional area, sq.in.
C	=	parameter defined in Equation 5
D	=	density, lb/gal
DI	=	riser internal diameter, in.
G	=	pressure gradient, psi/ft.
H	=	liquid hold-up, fraction
K	=	parameter defined in Equation 10
M	=	mass inside a cell, lbm
P	=	pressure, psi
SG	=	gas specific gravity, dimensionless
ST	=	gas/liquid surface tens., dynes/cm
t	=	time, sec.
T	=	temperature, degrees F
v	=	velocity, ft./sec.
x	=	length, ft.
Z	=	gas comp. factor, dimensionless

Subscripts

acc	=	acceleration
c	=	current time step
d	=	downstream
fri	=	friction
g	=	gas
hyd	=	hydrostatic
l	=	liquid
m	=	mixture
p	=	previous time step
sl	=	slip
u	=	upstream

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TABLE 01- EQUIPMENT AND FLUID PARAMETERS USED IN THE SIMULATIONS.

RISER LENGTH	3000 FT
RISER INSIDE DIAMETER	21 IN
DRILL PIPE OUTSIDE DIAMETER	5 IN
DIVERTER LENGTH	100 FT
DIVERTER INSIDE DIAMETER	6 IN
GAS DENSITY	0,7
SURFACE TENSION	70 DYNE/CM
MUD WEIGHT	8,5 PPG
FLOW BEHAVIOR INDEX	0,9
CONSISTENCY INDEX	0,004 LBF.SEC ⁰
TEMPERATURE	90 F
	SQ.FT

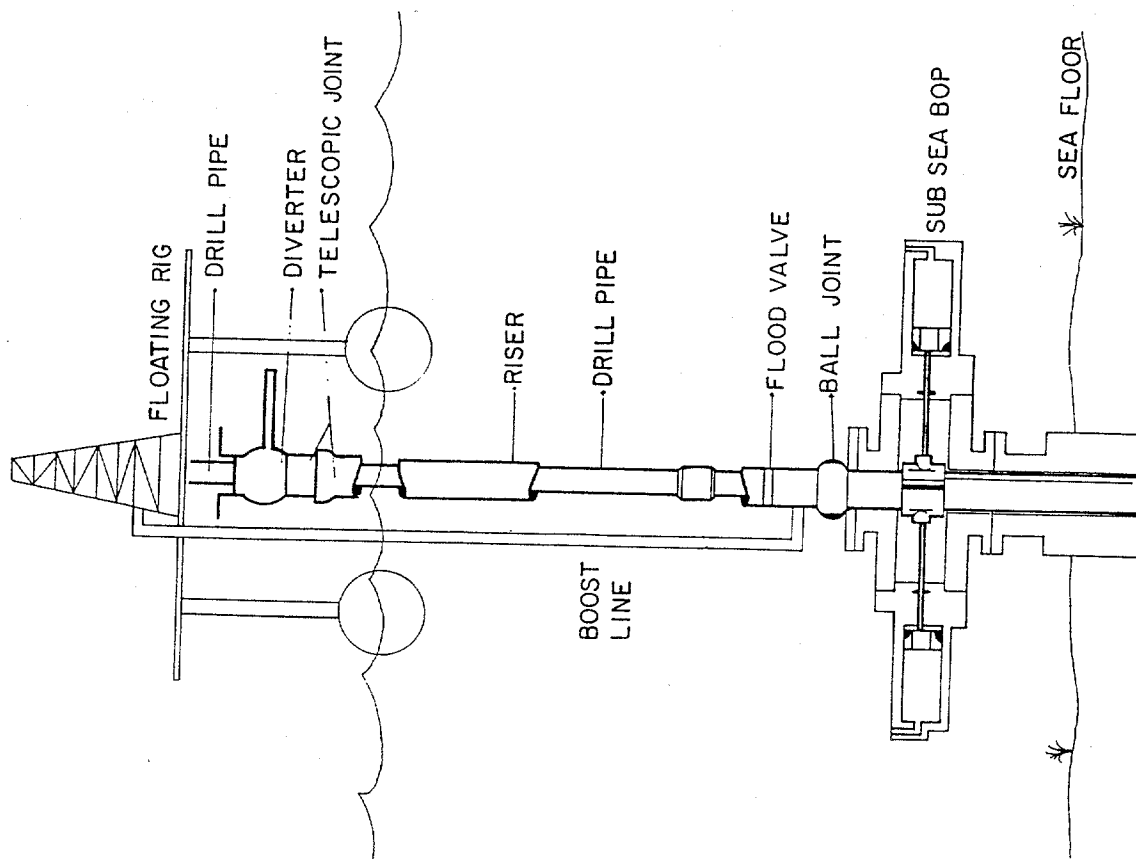


Fig. 01 - TYPICAL RISER SYSTEM

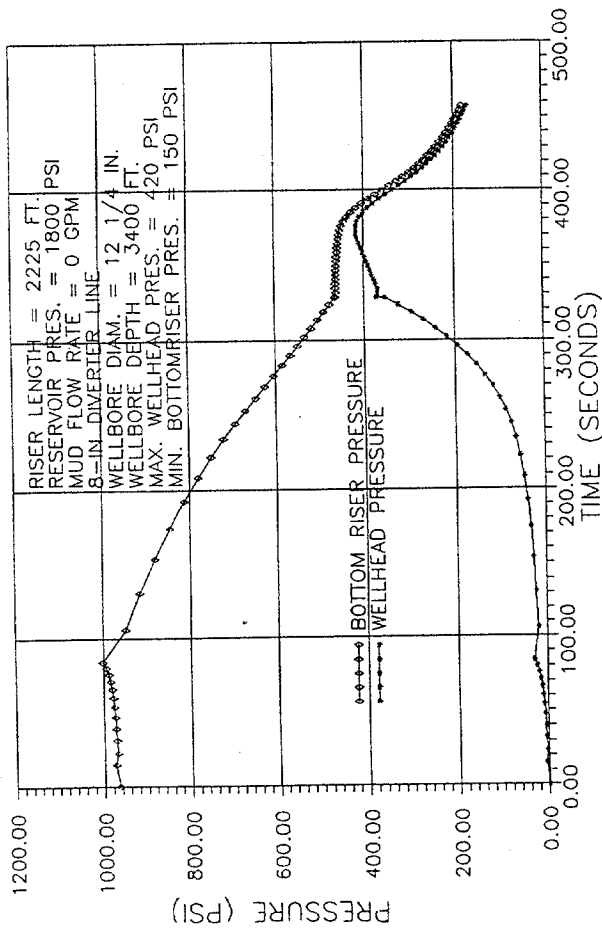


FIG. 02 - PRESSURES IN AN UNLOADED RISER

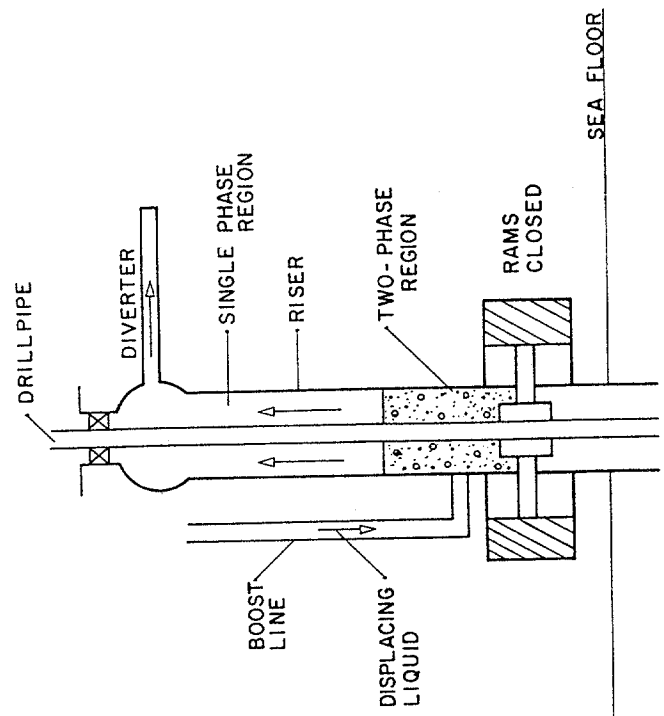


Fig. 03 - CIRCULATION OF KICK OUT OF RISER.

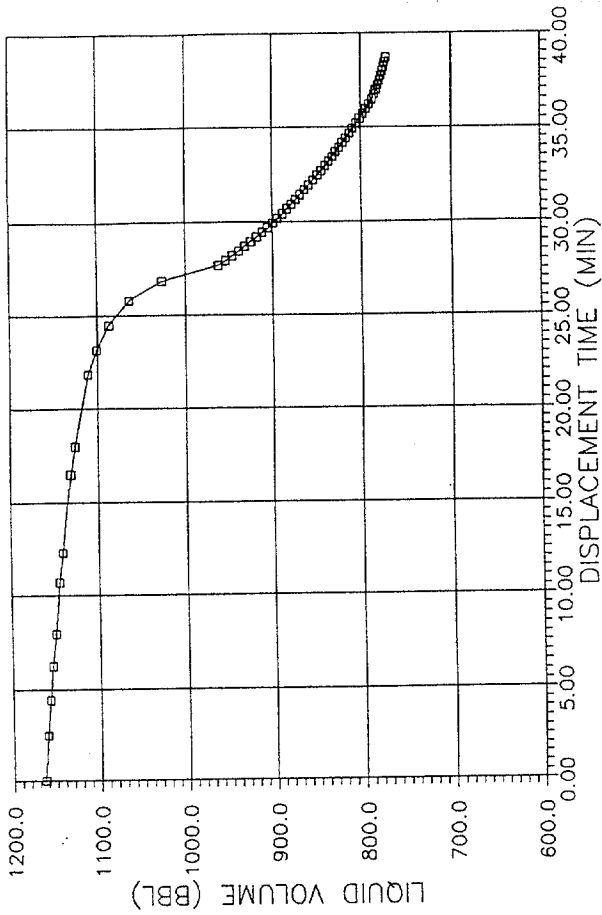


FIG. 04 - LIQUID VOLUME LEFT IN THE RISER FOR 50 BBL OF GAS

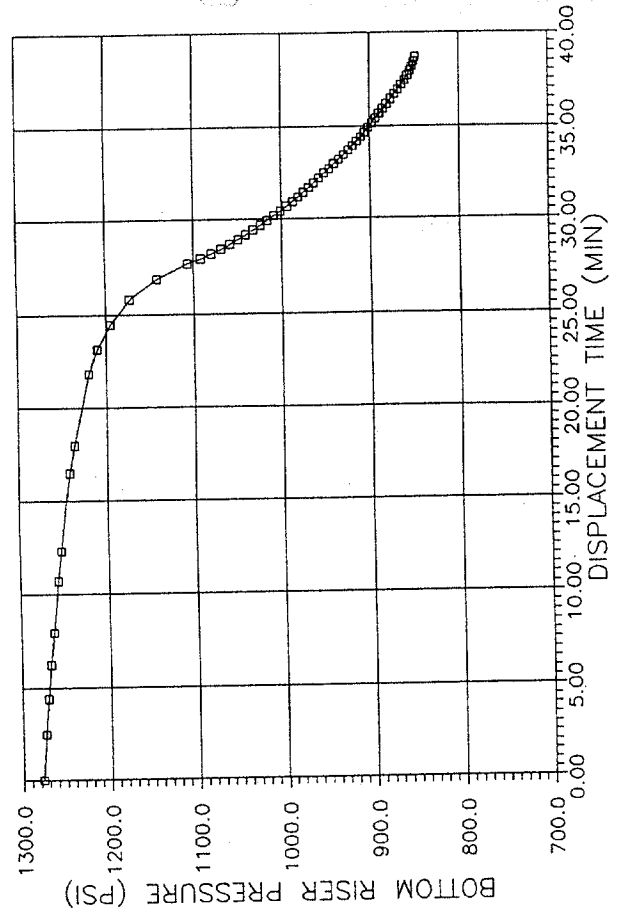


FIG. 05 - BOTTOM RISER PRESSURE FOR 50 BBL OF GAS

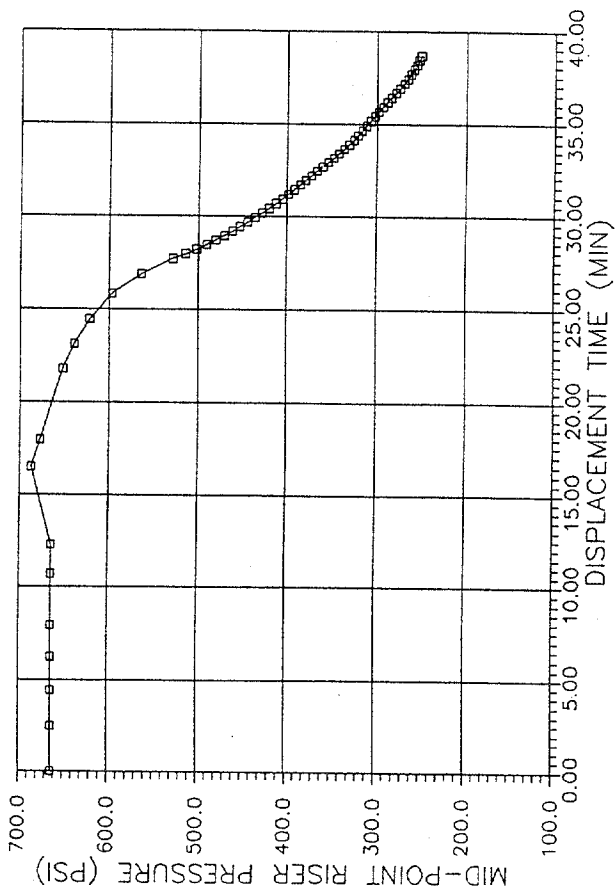


FIG. 06 - MID-POINT RISER PRESSURE FOR 50 BBL OF GAS

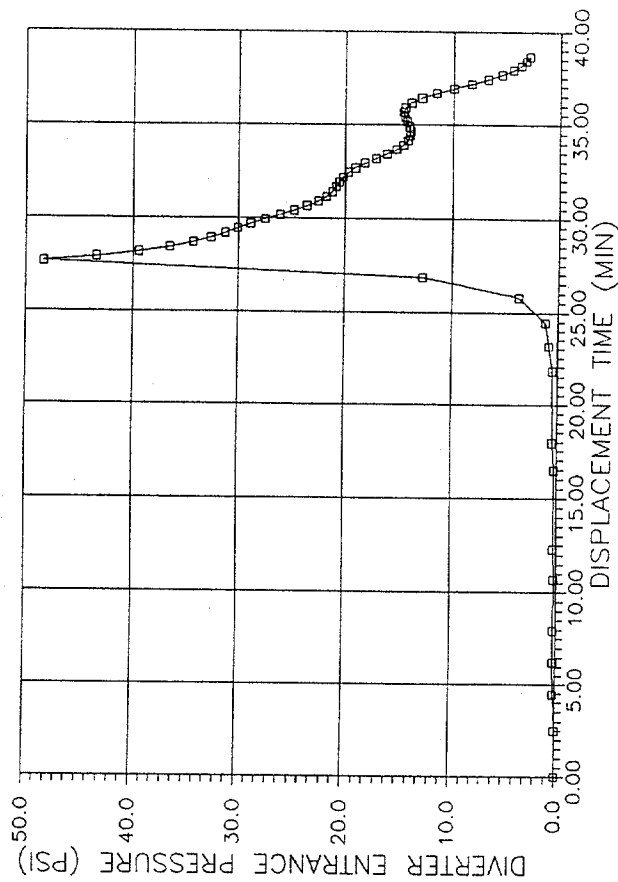


FIG. 07 - DIVERTER ENTRANCE PRESSURE FOR 50 BBL OF GAS

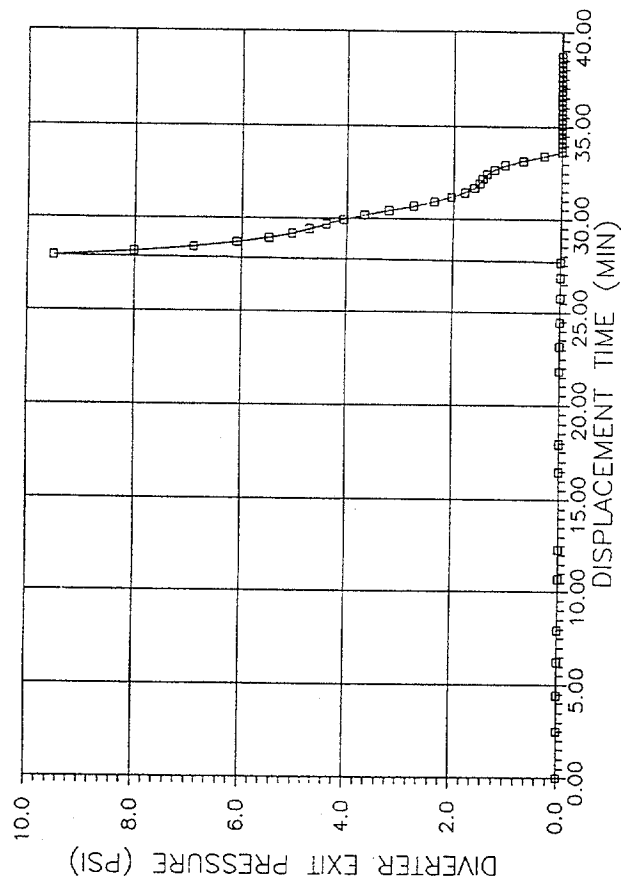


FIG. 08 - DIVERTER EXIT PRESSURE FOR 50 BBL OF GAS

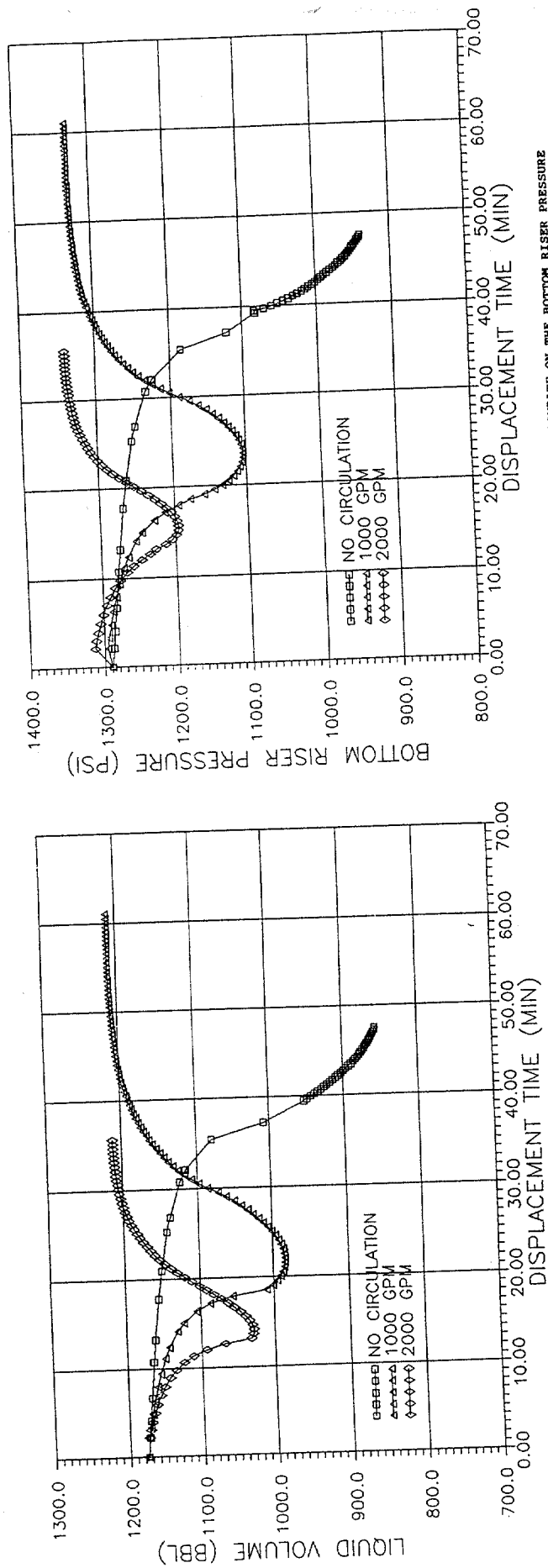


FIG. 9 - EFFECT OF FLOWRATE ON THE LIQUID VOLUME LEFT IN THE RISER

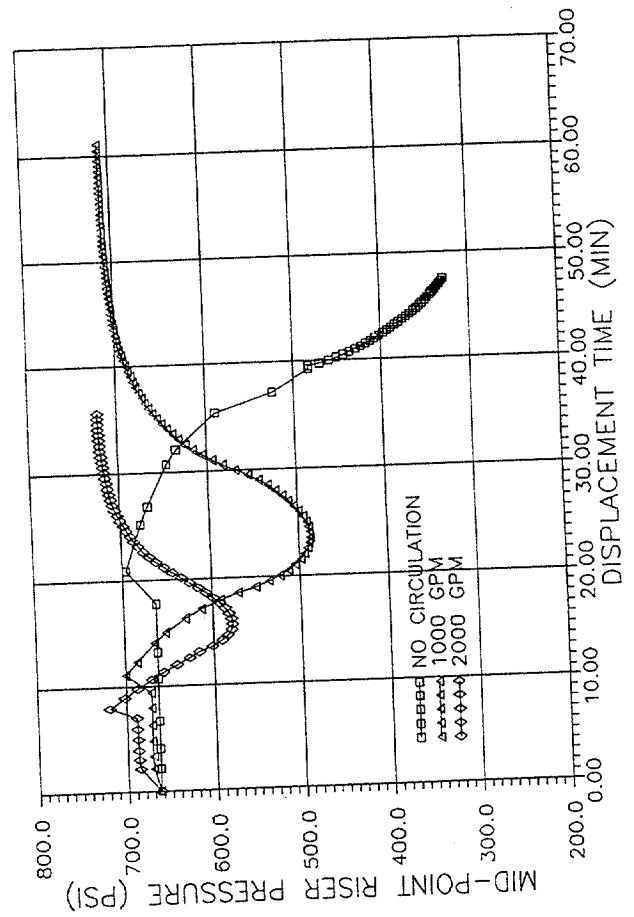


FIG. 11 - EFFECT OF FLOWRATE ON THE MID-POINT RISER PRESSURE

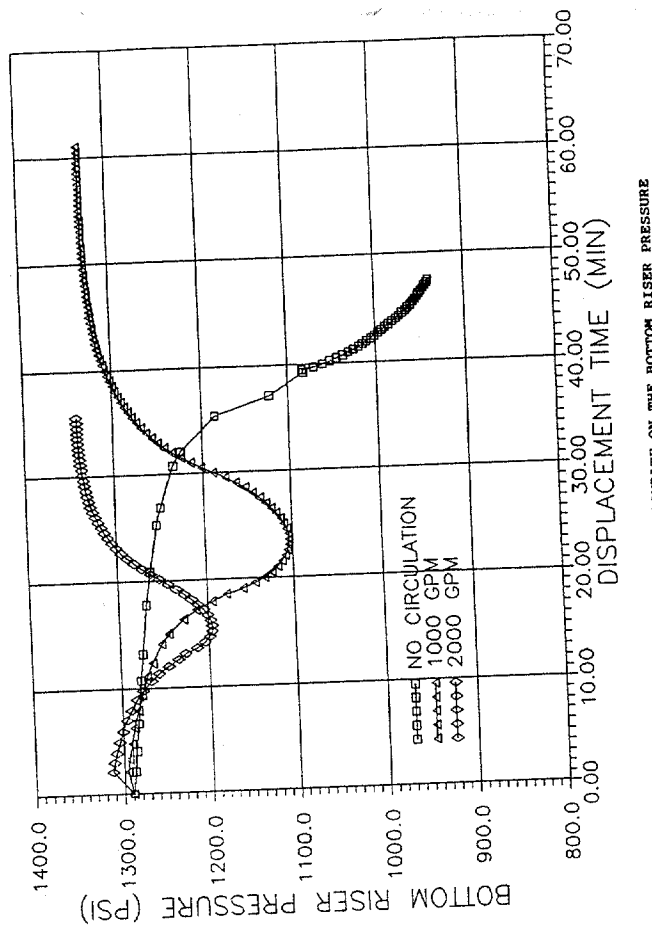


FIG. 10 - EFFECT OF FLOWRATE ON THE BOTTOM RISER PRESSURE

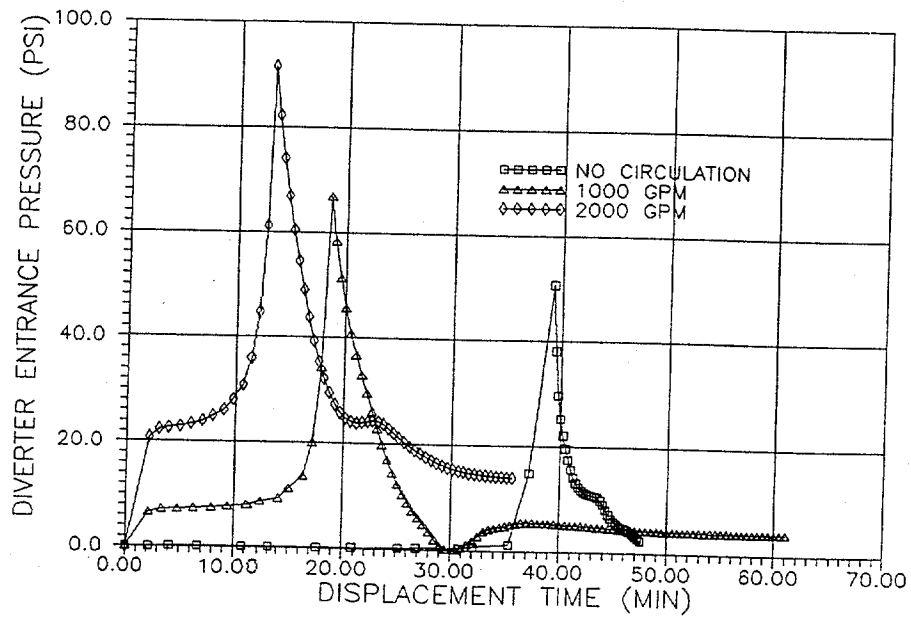


FIG. 12 - EFFECT OF FLOWRATE ON THE DIVERTER ENTRANCE PRESSURE

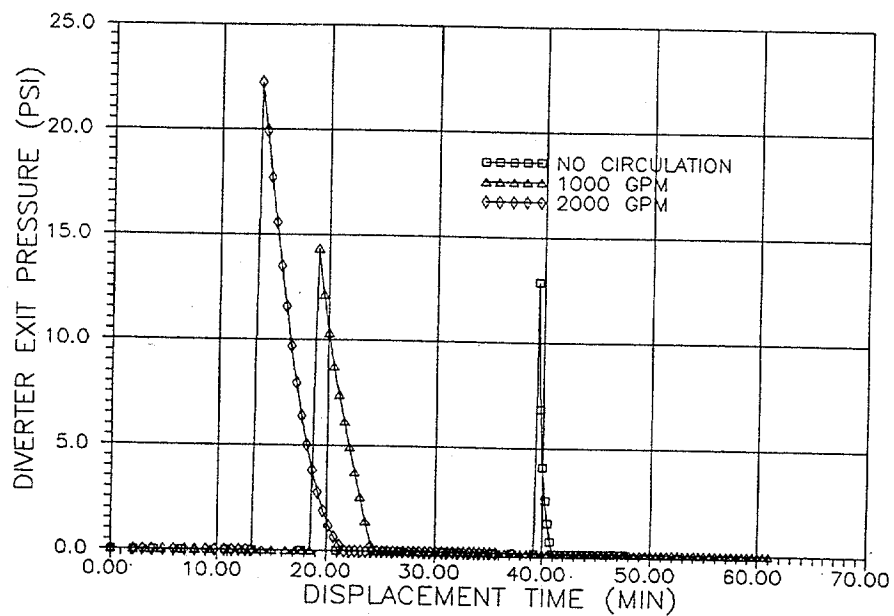


FIG. 13 - EFFECT OF FLOWRATE ON THE DIVERTER EXIT PRESSURE

Table 1

Recommended Values of Specific Erosion Factor (After Bourgoyne 4)

FITTING TYPE	CURVATURE RADIUS r/d	MATERIAL	GRADE	SPECIFIC EROSION FACTOR g/kg			
				DRY GAS FLOW		MIST FLOW	
ELBOW	1.5	Cast steel	WBC	2.2		2.8	
		Seamless steel	WPB		0.89		1.1
	2.0	Cast steel	WBC	2.0		2.4	
		Seamless steel	WPB		0.79		0.93
	2.5	Cast steel	WBC	1.7		2.0	
		Seamless steel	WPB		0.69		0.77
	3.0	Cast steel	WBC	1.5		1.65	
		Seamless steel	WPB		0.60		0.66
	3.5	Cast steel	WBC	1.2		1.32	
		Seamless steel	WPB		0.52		0.55
	4.0	Cast steel	WBC	0.9		1.0	
		Seamless steel	WPB		0.45		0.49
	4.5	Cast steel	WBC	0.7		0.77	
		Seamless steel	WPB		0.40		0.44
	5.0	Cast steel	WBC	0.5		0.55	
		Seamless steel	WPB		0.35		0.38
FLEXIBLE HOSE	6.0	Rubber	----	1.00		1.22	
	8.0	Rubber	----	0.40		0.45	
	10.0	Rubber	----	0.37		0.39	
	12.0	Rubber	----	0.33		0.35	
	15.0	Rubber	----	0.29		0.31	
	20.0	Rubber	----	0.25		0.28	
PLUGGED TEE	—	Cast steel	WBC	0.026		0.064	
	—	Seamless steel	WPB		0.012		0.040
VORTICE ELBOW	3.0	Cast steel	WBC	0.0078*			

* Assumes failure in pipe wall downstream of bend

The values presented in this table gave an average error of 29% which was felt to be acceptable for designing diverter systems. The error was based on the collected experimental data.

Verification for 6-in. Diameter.

Shown in Table 2 is a comparison of the measured erosion rates in the larger pipe size with those predicted by Equation (1). Note that the average error for these runs was 26%. These experimental data cover air and mist flow for the long, 1.5, curvature radius elbow.

Table 2

Comparison of Calculated and Measured Erosion Rates in 6-in. Diameter Diverter Systems

Erosion Rate							
R/d	Usl	Usg	Sand Rate	Fe	Calculated	Actual	Error
-	m/s	m/s	m ³ /s	kg/kg	m/s	m/s	-
1	0	30.9	432E-6	0.0021	2E-6	741E-9	112%
1	0	66.38	508E-6	0.0021	9E-6	8E-6	13%
1	0	76.59	509E-6	0.0021	11E-6	10E-6	19%
1	0	76.99	407E-6	0.0021	9E-6	8E-6	22%
1	0	77.68	273E-6	0.0021	6E-6	5E-6	38%
1	0	97.67	485E-6	0.0021	18E-6	16E-6	13%
1.5	0	59.44	807E-6	0.0014	7E-6	9E-6	-18%
1.5	0	61.68	352E-6	0.0014	3E-6	4E-6	-15%
1.5	0	98.43	578E-6	0.0014	14E-6	28E-6	-49%
1.5	0	99.39	844E-6	0.0014	21E-6	32E-6	-34%
1.5	0	101.7	128E-6	0.0014	3E-6	6E-6	-46%
1.5	0	103.2	328E-6	0.0014	9E-6	15E-6	-39%
1.5	0.00376	68.58	448E-6	0.0017	6E-6	7E-6	-10%
1.5	0.0125	68.7	470E-6	0.0017	7E-6	7E-6	3%
1.5	0.2274	88.15	717E-6	0.0017	17E-6	15E-6	16%
1.5	0.0125	100.8	497E-6	0.0017	16E-6	15E-6	7%
1.5	0.00376	101.49	516E-6	0.0017	16E-6	15E-6	10%

Seamless steel elbows, Grade WPB.

Combination of the new and old data yields slightly different average values for specific erosion rate factors. These modified recommended values are given in Table 3. A comparison of the observed and predicted values of erosion rate using these specific erosion rate factors are shown in Table 4. Note that the average error for all of the data is about 40 %. The same value is obtained by using the values presented in Table 1. However, the values recommended in table 3 yield better prediction for the larger diameters.

Table 3

Recommended Values of Specific Erosion Factor Based on 2-in. and 6-in. Diameter Diverter Systems

FITTING TYPE	CURVATURE RADIUS r/d	MATERIAL	GRADE	SPECIFIC EROSION FACTOR g/kg			
				DRY GAS FLOW		MIST FLOW	
ELBOW	1.0	Cast steel	WBC				
		Seamless steel	WPB		2.1		
	1.5	Cast steel	WBC	2.2		2.8	
		Seamless steel	WPB		1.4		1.7
	2.0	Cast steel	WBC	2.0		2.4	
		Seamless steel	WPB		0.79		0.93
	2.5	Cast steel	WBC	1.7		2.0	
		Seamless steel	WPB		0.69		0.77
	3.0	Cast steel	WBC	1.5		1.65	
		Seamless steel	WPB		0.60		0.66
	3.5	Cast steel	WBC	1.2		1.32	
		Seamless steel	WPB		0.52		0.55
	4.0	Cast steel	WBC	0.9		1.0	
		Seamless steel	WPB		0.45		0.49
	4.5	Cast steel	WBC	0.7		0.77	
		Seamless steel	WPB		0.40		0.44
	5.0	Cast steel	WBC	0.5		0.55	
		Seamless steel	WPB		0.35		0.38
FLEXIBLE HOSE	6.0	Rubber	----	1.00		1.22	
	8.0	Rubber	----	0.40		0.45	
	10.0	Rubber	----	0.37		0.39	
	12.0	Rubber	----	0.33		0.35	
	15.0	Rubber	----	0.29		0.31	
	20.0	Rubber	----	0.25		0.28	
PLUGGED TEE	—	Cast steel	WBC	0.026		0.064	
		Seamless steel	WPB		0.012		0.040
VORTICE ELBOW	3.0	Cast steel	WBC	0.0078*			

* Assumes failure in pipe wall downstream of bend

Table 4

Comparison of Calculated and Measured Erosion Rates on 2-in. and 6-in. Diameter Diverter Systems

Erosion Rate							
R/d	Usl	Usg	Sand Rate	Fe	Calculated	Actual	Error
-	m/s	m/s	m ³ /s	kg/kg	m/s	m/s	-
1	0	30.9	432E-6	0.0021	2E-6	741E-9	112%
1	0	66.38	508E-6	0.0021	9E-6	8E-6	13%
1	0	76.59	509E-6	0.0021	11E-6	10E-6	19%
1	0	76.99	407E-6	0.0021	9E-6	8E-6	22%
1	0	77.68	273E-6	0.0021	6E-6	5E-6	38%
1	0	97.67	485E-6	0.0021	18E-6	16E-6	13%
1.5	0	59.44	807E-6	0.0014	7E-6	9E-6	-18%
1.5	0	61.68	352E-6	0.0014	3E-6	4E-6	-15%
1.5	0	98.43	578E-6	0.0014	14E-6	28E-6	-49%
1.5	0	99.39	844E-6	0.0014	21E-6	32E-6	-34%
1.5	0	101.7	128E-6	0.0014	3E-6	6E-6	-46%
1.5	0	103.2	328E-6	0.0014	9E-6	15E-6	-39%
1.5	0.003761	68.58	448E-6	0.0017	6E-6	7E-6	-10%
1.5	0.0125	68.7	470E-6	0.0017	7E-6	7E-6	3%
1.5	0.2274	88.15	717E-6	0.0017	17E-6	15E-6	16%
1.5	0.0125	100.8	497E-6	0.0017	16E-6	15E-6	7%
1.5	0.003761	101.49	516E-6	0.0017	16E-6	15E-6	10%
1.5	0	32	17E-6	0.0014	409E-9	374E-9	9%
1.5	0	47	26E-6	0.0014	1E-6	332E-9	294%
1.5	0	72	45E-6	0.0014	5E-6	2E-6	229%
1.5	0	93	49E-6	0.0014	10E-6	4E-6	167%
1.5	0	98	45E-6	0.0014	10E-6	4E-6	137%
1.5	0	98	53E-6	0.0014	12E-6	5E-6	141%
1.5	0	103	53E-6	0.0014	13E-6	5E-6	148%
1.5	0	122	60E-6	0.0014	21E-6	34E-6	-39%
1.5	0	167	77E-6	0.0014	51E-6	37E-6	35%
1.5	0	169	94E-6	0.0014	63E-6	48E-6	32%
1.5	0	177	132E-6	0.0014	96E-6	83E-6	15%
1.5	0	177	110E-6	0.0014	81E-6	74E-6	10%
1.5	0	178	109E-6	0.0014	81E-6	65E-6	24%
1.5	0	203	112E-6	0.0014	108E-6	78E-6	39%
1.5	0	205	144E-6	0.0014	142E-6	80E-6	78%
1.5	0	222	114E-6	0.0014	131E-6	70E-6	87%
1.5	0	108	19E-6	0.0014	5E-6	4E-6	44%
1.5	0	109	35E-6	0.0014	10E-6	6E-6	72%
1.5	0	108	36E-6	0.0014	10E-6	5E-6	86%
1.5	0	104	58E-6	0.0014	14E-6	10E-6	46%
1.5	0	108	65E-6	0.0014	18E-6	14E-6	27%
1.5	0	108	75E-6	0.0014	21E-6	14E-6	56%
1.5	0	107	112E-6	0.0014	30E-6	14E-6	109%
1.5	0	111	145E-6	0.0014	41E-6	22E-6	85%
1.5	0	107	227E-6	0.0014	60E-6	36E-6	70%
1.5	0	106	240E-6	0.0014	63E-6	33E-6	93%
1.5	0	103	282E-6	0.0014	69E-6	30E-6	134%

Seamless steel elbows, Grade WPB

Conclusions

The study of multiphase flow trough diverters shows, in general, that the erosion rate for fluids containing abrasive solids:

- (1) Increases exponentially with the fluid flow rate for a given sand rate.
- (2) Increases linearly with sand flow rate for a given fluid flow rate.

Also, updated and extended specific erosion factors required to estimate erosion rates are presented in this work.

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Nomenclature

- A - Cross sectional area, m.
- d - Diameter, m.
- F - Specific factor, kg/kg.
- h - Thickness, m.
- q - Flow rate, m³/s.
- R - Curvature radius, m.
- u - Velocity, m/s.
- λ - Fractional volume or holdup.
- ρ - Density, kg/m³

Subscripts

- a - Abrasives.
- e - Erosion.
- g - Gas.
- l - Liquid.
- m - mixture.
- s - Steel, or superficial.
- w - Wall.

APENDIX A

SPE/IADC 18 716

EXPERIMENTAL STUDY

OF

EROSION IN DIVERTER SYSTEMS DUE TO SAND PRODUCTION

